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HUMAN THERMAL ANALYSIS OF TRAVERSE AND GEOLOGY TASKS DURING SIMULATED LUNAR EXTRAVEHICULAR ACTIVITY

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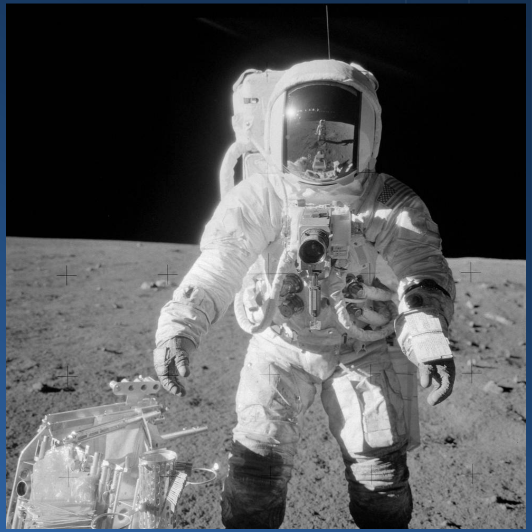
Motivation

- Learning to do Extravehicular Activities (EVA):
  - Gemini suits had limited thermal monitoring and cooling
    - Resulted in higher energy expenditure[1]
    - Life support capabilities were exceeded resulting in crew member fatigue[2]
  - Apollo EVAs implemented a liquid cooling garment (LCG) and metabolic rate calculations to monitor energy expenditure[2,3]
    - LCG Heat Balance (Inlet, Outlet, and assumed flow)
    - Heart Rate Approximations (Regressions from bicycle ergometer tests)
    - Oxygen consumption relation to delta pressure drop of O2

*Gemini 4 astronaut Ed White first microgravity EVA. Photo Credit: NASA



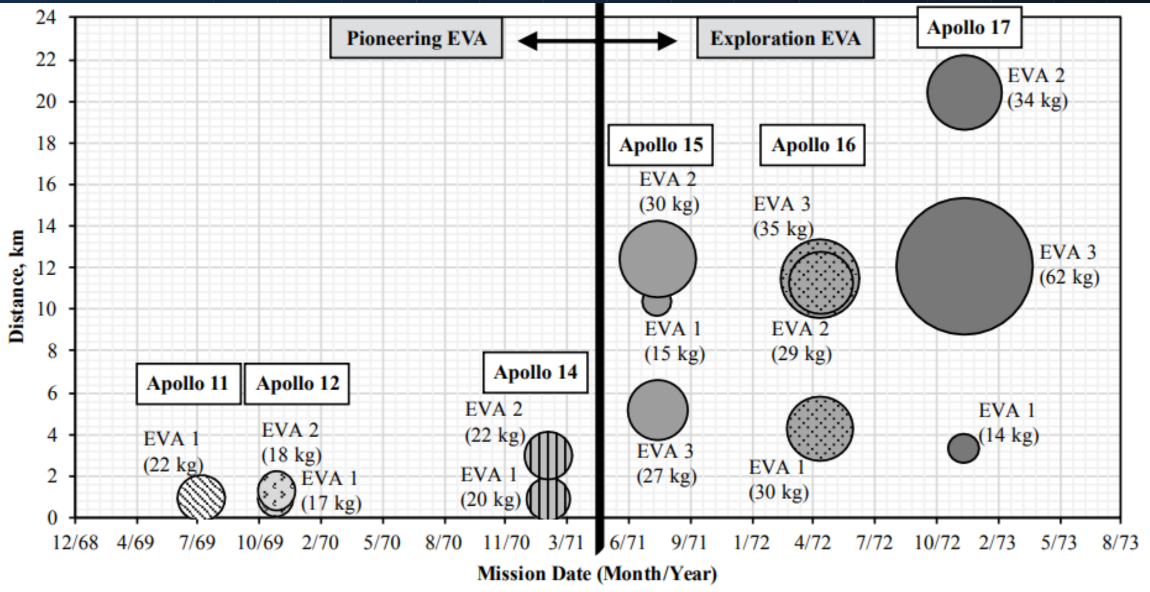
*Apollo 12 astronaut Alen L. Bean during surface EVA. Photo Credit: NASA

*Apollo LCG
Photo Credit: National Air and Space Museum

1. G. F. Kelly, D. O. Coons, and W. R. Carpentier, "Medical aspects of Gemini extravehicular activities," *Aerospace. Med.*, Jun. 1968.
2. H. Paul, "Energy Expenditure During Extravehicular Activity Through Apollo," ICES, 2012.
3. M. J. Miller, A. Claybrook, S. Greenlund, J. J. Marquez, and K. M. Feigh, "Operational Assessment of Apollo Lunar Surface Extravehicular Activity," NASA/TP-2017-219457

Motivation

- Lunar EVAs
  - During the Apollo program, 14 surface EVAs were completed across 6 missions[3]
    - Limited thermal data on Lunar surface
  - Traversing, geology, and science payload (object relocation) tasks were completed
    - Different metabolically demanding tasks
  - Near real-time flight control input and monitoring of energy expenditure.



* Apollo EVAs in distance traveled, mission date and size of samples being collected (bubble size).[3]

i. **Can we build methodology and data infrastructure to collect thermal standard measures for EVA ground testing?**

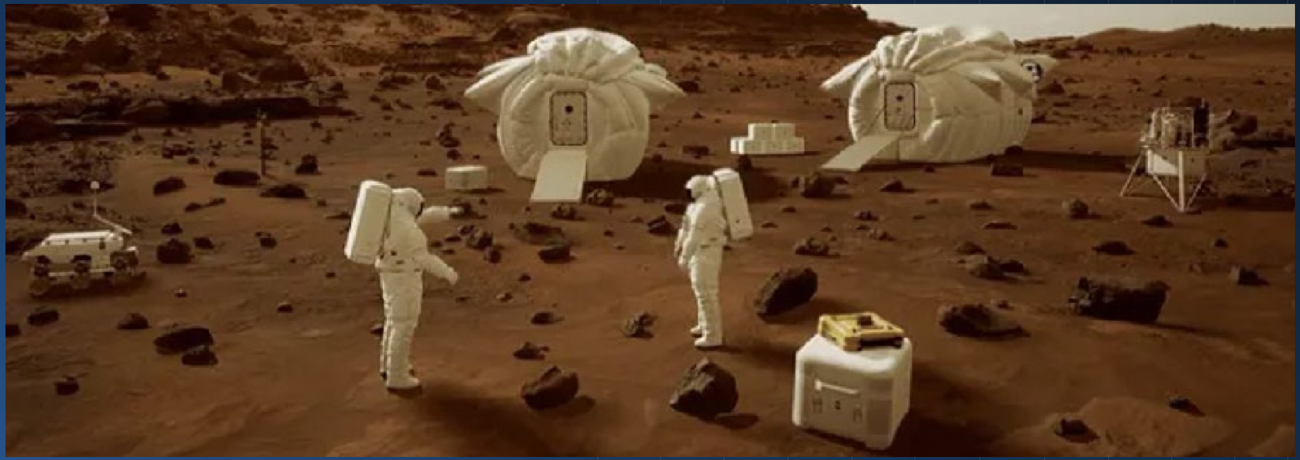
ii. **Can we differentiate which surface exploration tasks are high thermal drivers?**

3. M. J. Miller, A. Claybrook, S. Greenlund, J. J. Marquez, and K. M. Feigh, “Operational Assessment of Apollo Lunar Surface Extravehicular Activity,” NASA/TP-2017-219457

Motivation

- Future exploration class EVAs may be more physically demanding
  - Partial gravity shifts
  - EVA cadence
  - Exploration tasks

- Future exploration class missions will need more EVA autonomy.
  - Less reliance on mission control



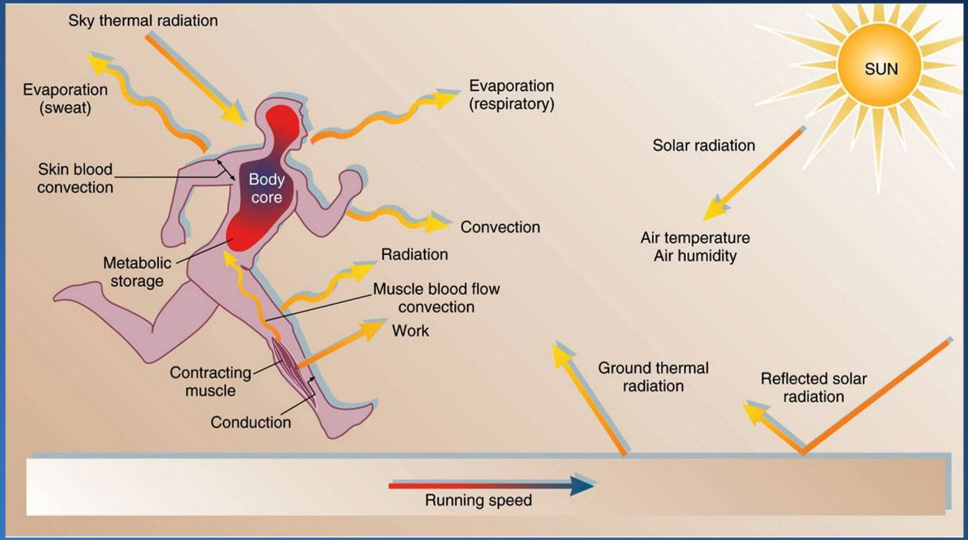
* Mars Mission Virtual Reality EVA testing. Photo Credit: NASA

iii. From standard measures ground testing, can we predict human thermal state for EVA readiness?

➢ **Through Crew State Risk Model predictions**

Background

Heat Exchange Mechanisms During Exercise



* [6,7]

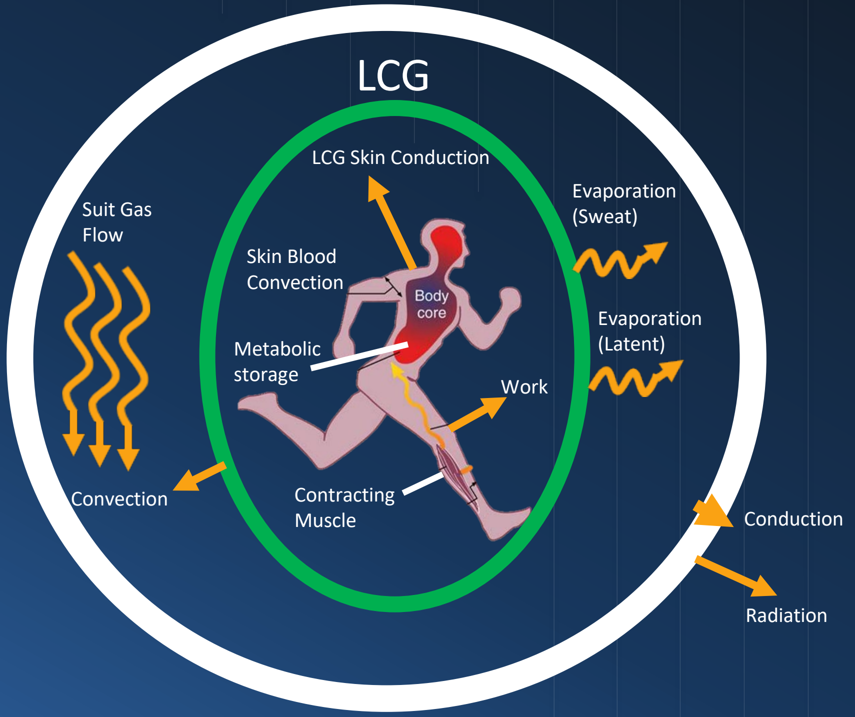
HOW TO ASSESS EACH COMPONENT OF THE HEAT BALANCE EQUATION THROUGH PARTITIONAL CALORIMETRY

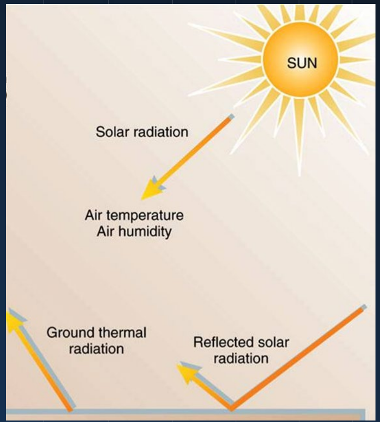
The fundamental human heat balance equation states

$$S = M - Wk - R - C - K - E\ (W)$$

* S is the rate of body heat storage. M is metabolic rate, Wk is external work rate, R is radiation, C is convection, K is conduction, and E is evaporation

Heat Exchange Mechanisms During EVA





- Loss of natural convection
- Conduction through LCG
- Limited Evaporation capability

6. Powers, S. K., Howley, E. T., & Quindry, J. "*Exercise physiology: Theory and application to fitness and performance*" New York, NY: McGraw-Hill, 2007
7. Cramer, M. N., & Jay, O., "Partitional calorimetry." *Journal of applied physiology*, 2019

Methods

- Suited Testing Environment
  - Active Response Gravity Offload System (ARGOS)
    - 1/6-g offloading
  - Subjects Donned the Mark III (MK-III) prototype planetary space suit
    - Subjects donned full-body LCG prior to suit donning

- Subject Data Pilot Study
  - Two healthy male subjects
  - Both subjects had MK-III suited experience
  - Approved by NASA Johnson Space Center IRB

Methods

- Simulated EVA Test Setup
  - End-to-end EVA circuit consisting of:
    - Treadmill Traverses (A)
    - Object Relocation Tasks (B)
      - Trailor to simulated rocky terrain
    - Geology Tasks (C)
      - Trailor to simulated surface geology
  - Break
  - Stand alone geology tasks
    - Two-minute break between tasks

EVA Task Circuit	Time (min)
Baseline	≈25
Lander Platform	1
1500m Traverse- Varied negative grades (−5%, −7%, and −10%)	≈30
Geology (Slope 0°)	15
500m Traverse (30% grade)	≈10
Geology (Slope 10°)	15
500m Traverse (20% Grade)	≈10
Object Relocation	15
10 lb small and large	6
20 lb small and large	6
500m Traverse (10% Grade)	≈10
BREAK	30
2000m Traverse- Varied grades (-10% to +30%)	≈45
Geology Rake	5
Geology Trench	5
Geology Float Sample	5
Geology Scoop	5
Geology Sample Tagging	5
Geology Drive Tube	10

(A)

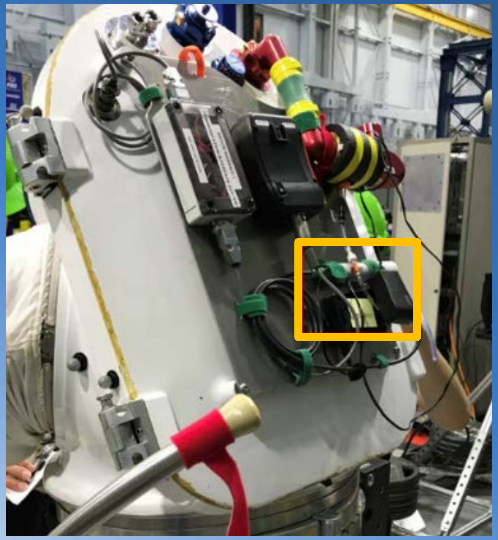
(B)

(C)

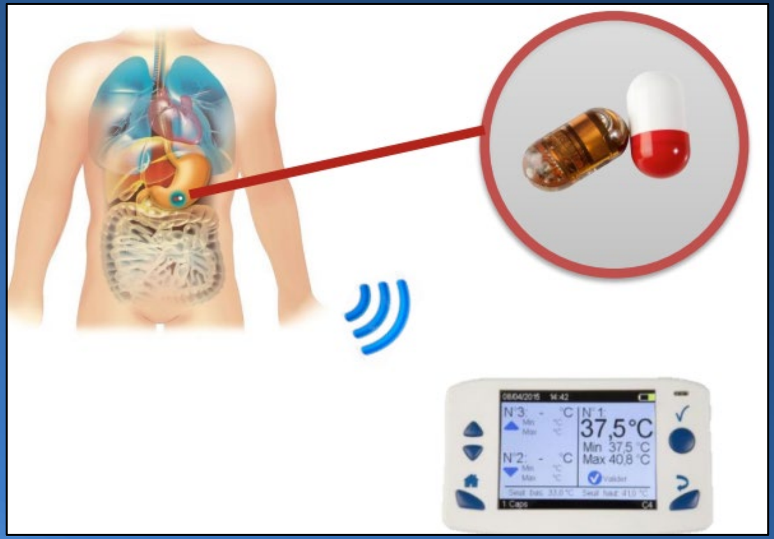
Methods

- Sensor Instrumentation Setup
  - Physiology Metrics:
    A. Expired CO2 (Vaisala GMP252)
    B. Core body temperature (BodyCap)
    C. Local skin temperature (iButton, 6 locations)

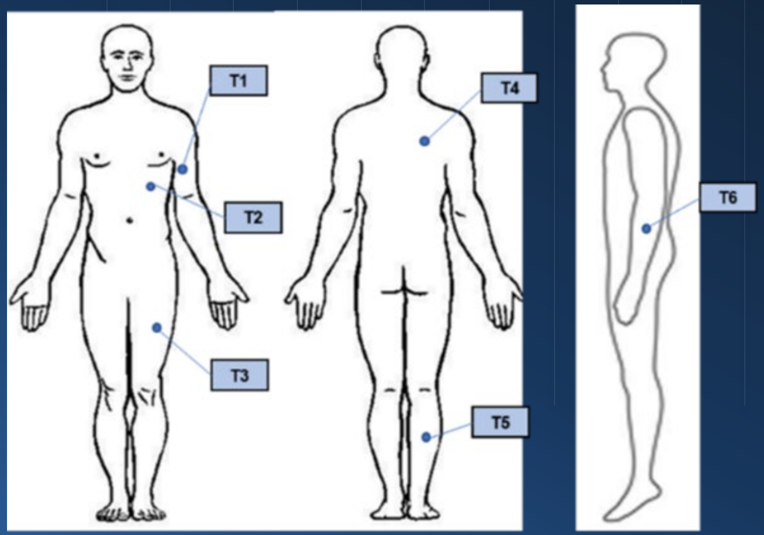
A.



B.



C.

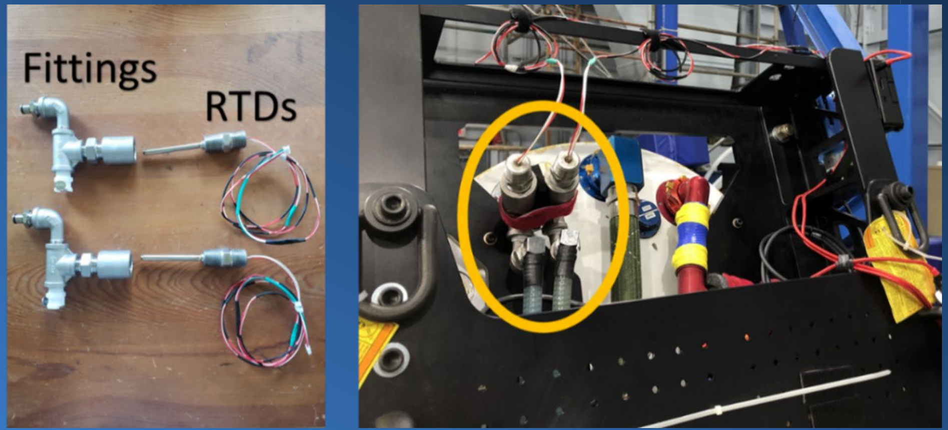


Methods

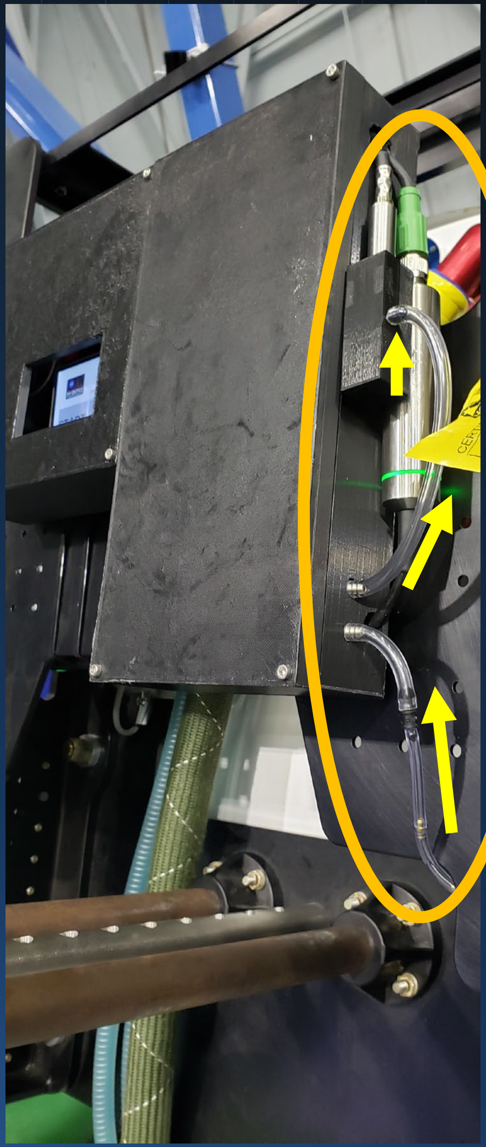
- Sensor Instrumentation Setup
  - A. Suit inlet temperature and humidity (iButton)
  - B. LCG inlet and outlet temperature (Resistive Temperature Detector)
  - C. Suit outlet temperature and humidity (Vaisala HMP7)

A.

B.



C.



Methods

- Data Analysis:
  - Task Blocks:
    - Tasks were divided into six blocks for analysis (Color coded).
    - Each block represented traverse and activity.
  - Metabolic Rate calculation was completed using the Péronnet Formula[4] (Eq. 1):

$$Energy\ Expenditure \left(\frac{BTU}{hr}\right) = 60 * 3.97 * \left(\frac{4.039 * VCO_2}{RER} + 1.157 * VCO_2\right) \quad (1)$$

  - Mean Skin Temperature was calculated via the Ramanathan method[5] (Eq. 2):

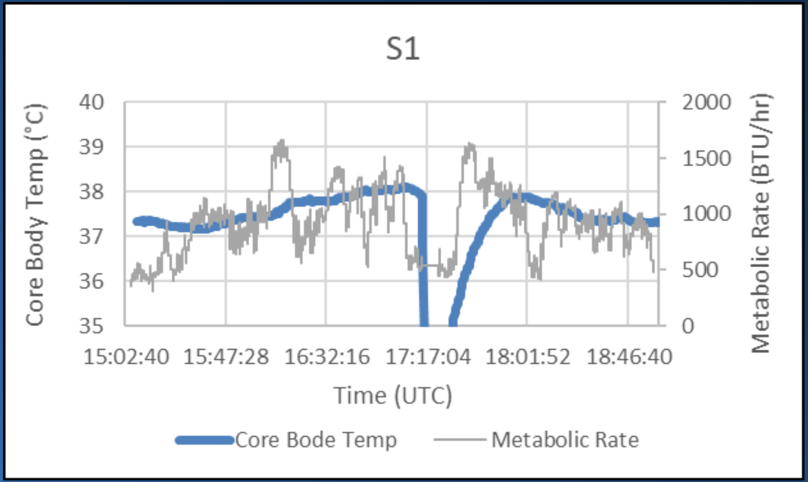
$$Ts\ (°C) = 0.3 * (Chest + Bicep) + 0.2 * (Quadricep + Calf) \quad (2)$$

  - Delta temperatures were calculated between LCG water and MK-III suit gas inlet and outlets.
  - Task Averages were calculated over the task block to view overall changes in:
    - Core temperature
    - Mean skin temperature
    - Suit LCG delta temperature
    - Suit gas delta temperature and humidity

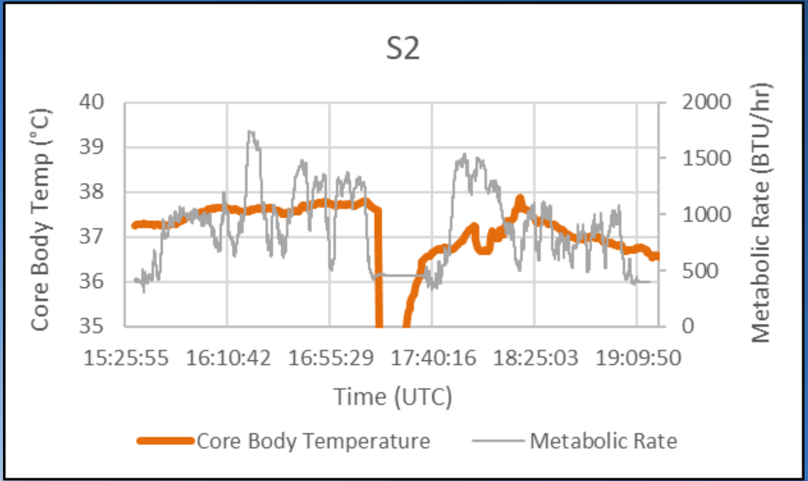
	EVA Task Circuit	Time (min)
Task Block 1	Baseline	≈25
	Lander Platform	1
Task Block 2	1500m Traverse- Varied negative grades (−5%, −7%, and −10%)	≈30
	Geology (Slope 0°)	15
Task Block 3	500m Traverse (30% grade)	≈10
	Geology (Slope 10°)	15
Task Block 4	500m Traverse (20% Grade)	≈10
	Object Relocation	15
	4.5 Kg small and large	6
	9 Kg small and large	6
	500m Traverse (10% Grade)	≈10
Task Block 5	BREAK	30
Task Block 6	2000m Traverse- Varied grades (-10% to +30%)	≈45
	Geology Rake	5
	Geology Trench	5
	Geology Float Sample	5
	Geology Scoop	5
	Geology Sample Tagging	5
	Geology Drive Tube	10

4. F. Péronnet and D. Massicotte, "Péronnet F, Massicotte DTable of nonprotein respiratory quotient: an update. Can J Sport Sci 16:23-29," *Can. J. Sport Sci. J.*, 1991.
5. D. Mitchell and C. H. Wyndham, "Comparison of weighting formulas for calculating mean skin temperature," *J. Appl. Physiol.*, 1969

Results



* LCG offloaded average 1250 BTU/hr

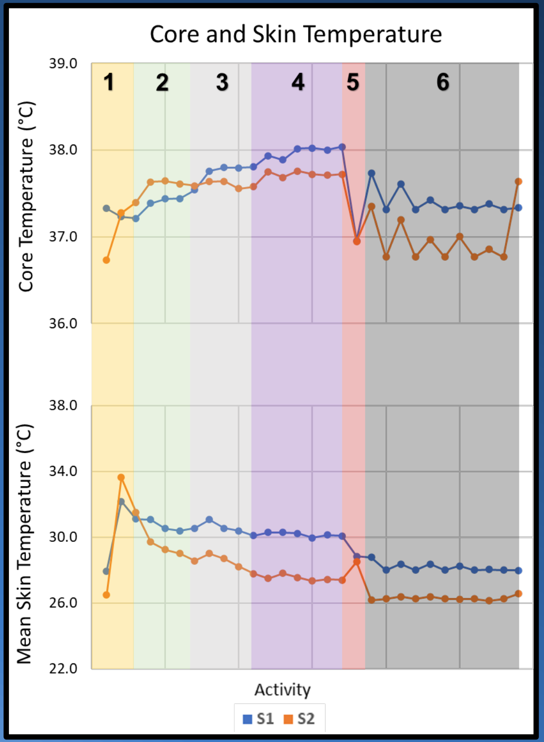


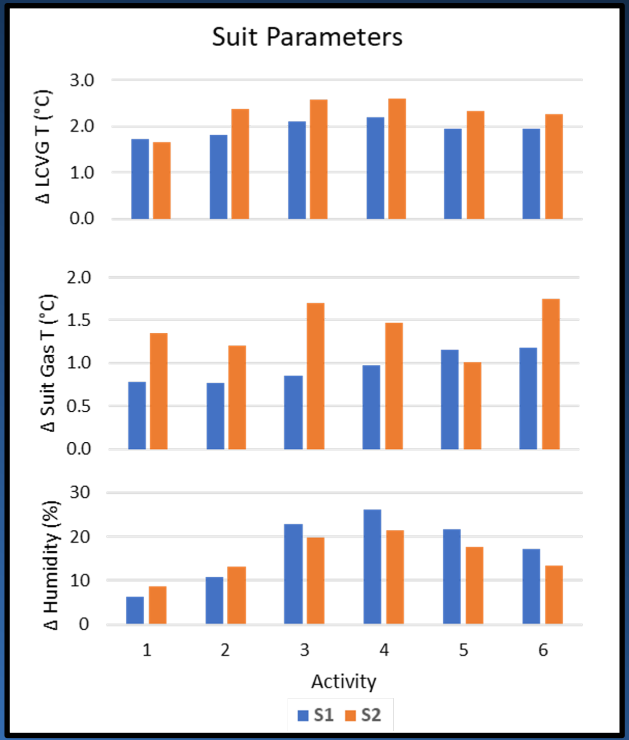
* LCG offloaded average 800 BTU/hr

EVA Task Circuit	Metabolic Rate		Core Temperature		Mean Skin Temp		Delta LCG		Delta Suit Humidity	
	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Baseline	534	422	37.3	36.7	27.9	26.5	1.8	2.0	5.7	9.4
Lander Platform	601	435	37.2	37.2	32.2	33.6	1.6	1.3	7.0	7.8
1500m Traverse- Varied negative grades (−5%, −7%, and −10%)	917	944	37.2	37.3	31.1	31.5	1.9	2.2	9.7	11.5
Geology (Slope 0°)	913	870	37.4	37.6	30.7	29.3	1.7	2.4	11.1	13.9
500m Traverse (30% grade)	1387	1279	37.5	37.6	31.1	28.6	2.1	2.6	22.1	18.7
Geology (Slope 10°)	881	944	37.8	37.6	30.1	28.6	2.1	2.6	23.1	20.0
500m Traverse (20% Grade)	1200	1191	37.8	37.6	30.1	27.8	2.1	2.5	24.2	19.8
Object Relocation										
4.5 Kg small and large	1145	1225	37.9	37.7	30.3	27.7	2.2	2.6	26.4	23
9 Kg small and large	1093	1121	38.0	37.7	30.0	27.4	2.2	2.6	25.8	21.2
500m Traverse (10% Grade)	1170	1179	38.0	37.7	30.1	27.4	2.2	2.7	28.3	22.3
BREAK	585	492	34.0	35.4	29.7	27.6	2.0	2.3	21.6	17.6
2000m Traverse- Varied grades (-10% to +30%)	1209	1195	37.0	37.0	28.8	28.5	2.1	2.4	24.0	20.1
Geology Rake	933	903	37.7	37.3	28.8	26.2	2.0	2.4	20.0	14.4
Geology Trench	977	723	37.6	37.2	28.3	26.3	2.0	2.2	19.6	13.0
Geology Float Sample	898	718	37.4	37.0	28.3	26.4	1.9	2.3	18.9	11.1
Geology Scoop	814	783	37.4	37.0	28.2	26.2	1.9	2.2	17.2	12.0
Geology Sample Tagging	922	839	37.4	36.9	28.0	26.1	1.9	2.2	17.4	13.0
Geology Drive Tube	847	834	37.3	37.6	28.0	26.6	1.9	2.4	15.3	15.2

Results

- Core body temperature, mean skin temperature and suit metrics across the 6 task blocks:





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- Core body temperature compounded as the simulated tasks progressed.
- Mean skin temperature sharply rose but slowly decreased as heat was rejected to LCG.
- Suit delta LCG and delta humidity had noticeable changes between task blocks following the increasing core body temperature trend.
- Suit gas delta temperature varied between subjects.

Discussion

- This study demonstrated feasibility in collecting thermal standard measures during suited ground testing.
- Core temperature is a compounding metric: Metabolically demanding tasks will produce heat that will continually drive-up core body temperature unless offloaded.
  - *Gathering more core body temperature values during suited analog EVAs will aid in identifying thermally sensitive exploration tasks.*
- LCG temperatures and suit gas temperature and humidity are dependent on the suited configuration.
  - *Applying suited thermal standard measures are recommended to collect suit heat offloading metrics that will aid in determining nominal heat storage, mean skin temperature, and core body temperature values.*
- Traverse tasks are high metabolic drivers, in turn producing the most heat.
  - *Human thermal measures can aid in EVA planning by dividing the EVA into manageable tasks that do not compound heat storage.*

Limitations and Future Work

- Core temperature capsules were given the day of testing. During scheduled breaks drinking water affected the core body temperature measurement. Future studies should give the capsule the day prior.

- A single suited configuration was used in this study. Future analogs can be used to broaden the human thermal data and heat offloading in a suited environment.

- LCG flow rate was an assumed flow rate. Future studies will involve measured feedwater flow rate for heat balance.

- Future work will incorporating thermal standard measures to capture more data needed to develop the Crew State and Risk Model predictions of EVA readiness and EVA heat loading risks.
  - For predictive core temperature and heat storage capability.

Acknowledgments

- *Human Physiology, Performance, Protection and Operations Team*
  - Taylor Schlotman
  - Lauren Cox
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  - Patrick Estep
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  - Zach Wusk
  - Monica Hew
  - Rachel Thompson
  - Katie Heinemann
- *Advanced Suit Lab Team*
- *ARGOS Team*
- *Medical Monitoring*
- *Suited Subjects*

This work was funded by NASA Exploration Capabilities

Thank you.

Backup

CSRM

Measurement Updates
(variable refresh rate)
- Suit Data
- Environmental Data
- Physiologic Monitor
- Time delta

Simulator Updates
When full data set is not available:
- APACHE
- ARGOS
- NBL
- B21 HighBay
- Tabletops
- Other analogs/sims

Algorithms

- Met Rate
- Thermal
- Fatigue
- piCO2
- DCS
- Traverse
- Hydr’n

Current State

- Measured Variables
- Calculated Variables

Predicted State

Decision Maker

CSRM

Thermal (Orange) and Metabolic Rate (Blue) Model Concepts